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F2 BOUNDARY LAYER MEASUREMENT IN A CHEMICAL LASER SLIT

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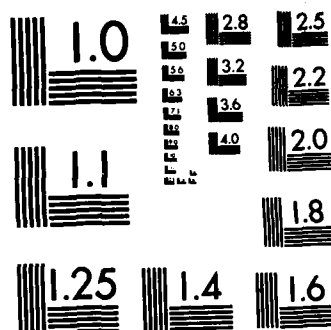
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F₂ Boundary Layer Measurement in a Chemical Laser Slit Nozzle Flow

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15 February 1983

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

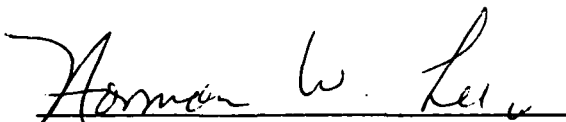


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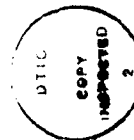
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I. BACKGROUND

The presence of recombined F_2 in the boundary layers of chemical laser nozzle flows has been considered to be a source of laser inefficiency.^(1,2) This inefficiency was thought to derive from (1) the reduction of F atom concentrations that contribute to lasing, (2) the inhibition of H_2 mixing with the F atoms, and (3) the deleterious temperature rise produced in the flow by H atom reactions with F_2 . The uncertainties in the magnitudes and distributions of the F_2 molecules in the nozzle flows have hampered modeling of chemical laser performance based on this assumption, however. In response to this situation, a sensitive F_2 absorption diagnostic was developed capable of detecting fractions of a percent of the associated F atom concentrations in the flows. This diagnostic device has been used in the past to probe the flows of arc-driven SF_6 and F_2 ⁽³⁾ and combustor-driven F_2 ⁽⁴⁾ chemical laser nozzle flows, and to establish their total F_2 recombination operational levels. Fig. 1 is a system schematic of the technique employed in these past studies. A Liconix Model 301M HeCd intracavity acousto-optic modulated laser operating at 325 nm was employed to probe the F_2 concentrations in the absorption measurement region. The difference between the probe beam and reference beam intensities was measured with two independent silicon photovoltaic detectors and displayed on an oscilloscope for conditions of F_2 present or F_2 absent from the measurement region. The laser was square wave modulated at ~ 20 Hz by an Interstate Electronics Model P25 pulse generator. The pulse generator also provides an external sync signal for the Tektronix Model 545 scope, which has a Tektronix Model 1A7A 10- μ V sensitivity differential plug-in

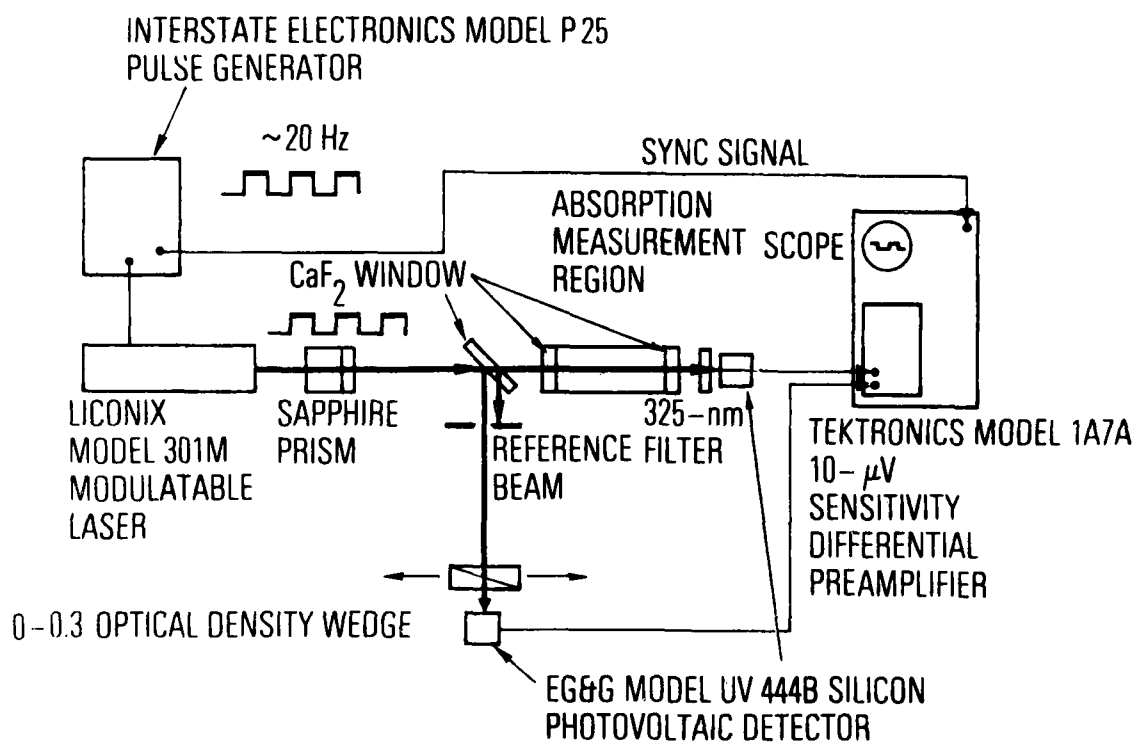


Fig. 1. Sensitive F_2 absorption technique schematic

amplifier. The modulated laser beam is passed through a sapphire prism before beam splitting at a CaF_2 window to eliminate the weak horizontally polarized beam from the optical path.

A narrowband 325 nm wavelength optical filter discriminates against measurement by the probe beam detector of other wavelengths generated in the absorption measurement region. An optical density wedge is used for refined intensity variation of the reference beam to obtain zero differential signal between the probe and reference beams, as measured on two EG and G Model UV 444B silicon photovoltaic detectors, for the condition of no F_2 in the measurement region.

The differential intensity measurement ΔI made upon F_2 addition to the measurement region, coupled with the probe beam initial intensity measurement I_0 and the absorption path length L , allows calculation of the F_2 density directly from the equation

$$\rho_{\text{F}_2} (\text{mole/l}) = (1/8.70 L (\text{cm})) (\Delta I/I_0) \quad (1)$$

For further details of this measurement method, see Refs. (3) and (4).

II. EXPERIMENTAL SETUP

In the present study, a 15 mW Liconix Model 405V (UV) laser was employed to increase signal-to-noise ratio and provide a TEM_{00} beam for reduced beam size. (The model 301M laser operates at 1 mW on the TEM_{01} mode.) The F_2 diagnostic was used for measurements across the entire nozzle array jet to verify the diagnostic prior to the more complex slit nozzle scanning tests. In addition, measurements across the jet near the nozzle exit plane and 1-1/2 inches downstream were made to establish the total F_2 loss in passage through the jet. A photograph of the experimental array as used in absorption measurements across the jet is shown in Fig. 2. The F_2 absorption diagnostic was modified to provide 0.006 inch diameter resolution over a 1-1/2 inch path length for scanning of slit nozzle flows to determine the F_2 boundary layer profile. The modifications consisted of adapting the probe beam to the geometrical constraints imposed on the experiment by the slit nozzle flow. Details of the absorption measurement region for the slit nozzle F_2 absorption scanning experiment are shown in Fig. 3. The drawing orientation allows one to view the vertically oriented slit nozzle array from a position downstream along the flow axis. The 18 inch square test section enclosure is shown crosshatched with 9 inch windows at cutouts on the sides and top. The probe beam from the laser on the right enters the test section horizontally through the 14 inch focal length quartz lens and a vacuum sealed CaF_2 window. A first surface folding mirror oriented at 45° within the test section directs the beam upward past the slit nozzle array through a vacuum sealed CaF_2 window to the translatable 325 nm filter-detector assembly mounted on top of the test

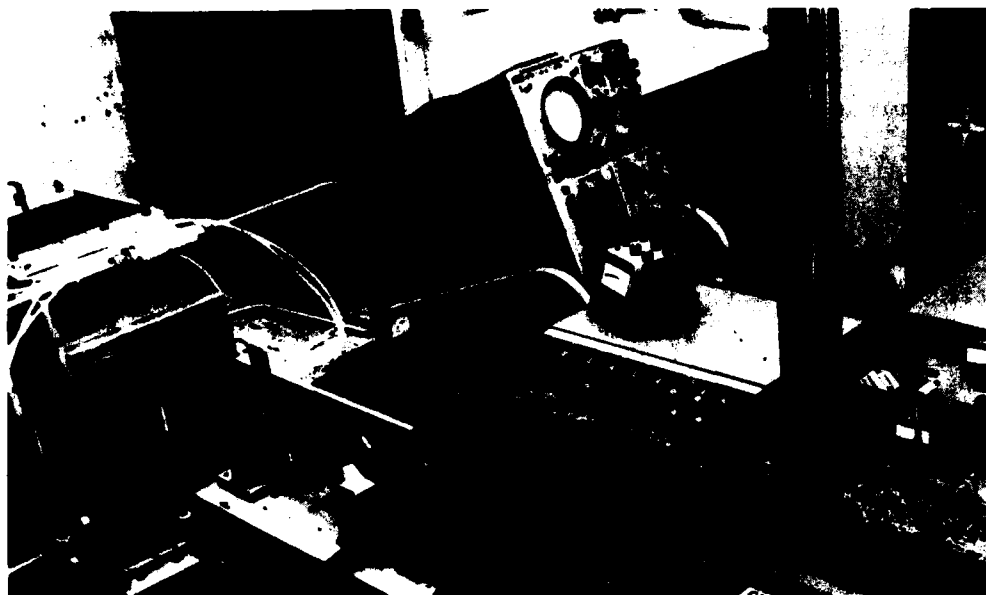


Fig. 2. Experimental array used in measurements across jet

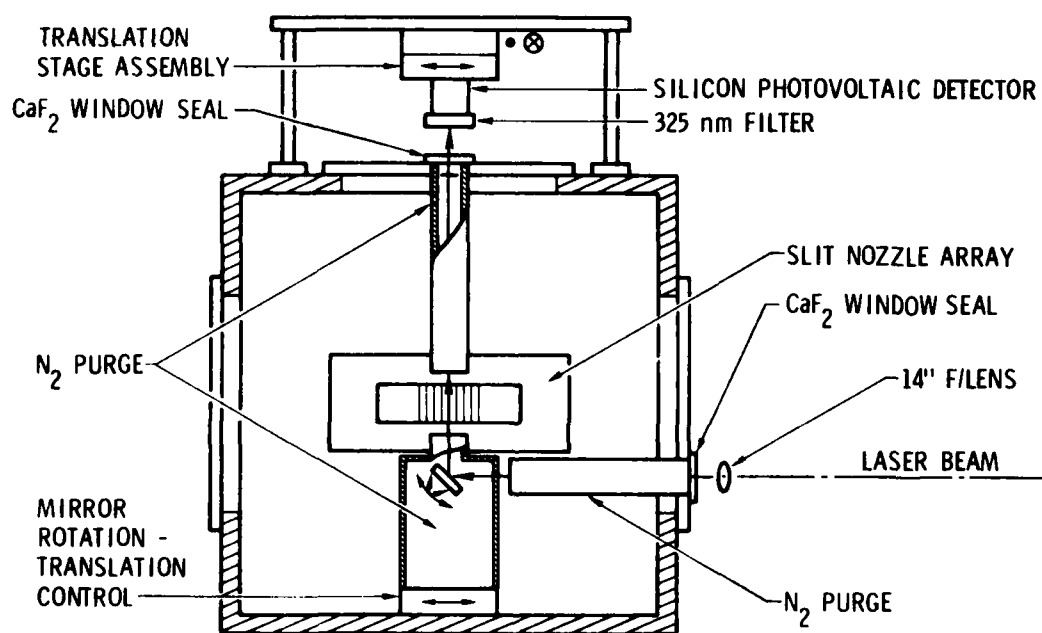


Fig. 3. Slit nozzle F_2 absorption scanning experiment

section. The 45° folding mirror is mounted on a translation stage controllable from outside the test section via flexible coupling cable for micrometer movement across the jets. In addition, the mirror mount provides the mirror with two degrees of freedom rotational alignment capability. The mirror housing and ducts along the optical path are positioned within 1/8 inch of the jet and purged with N₂ so as to confine the measurement distance to the slit nozzle length. Intensity sensitivities of $\Delta I/I_0 = 3 \times 10^{-5}$ were obtained with this system. This detection sensitivity corresponds to a lower limit measurability of ~ 15 milli Torr F₂ at T ≈ 300°K over the 1-1/2 inch absorption path length of this experiment. Beam alignment parallel to the nozzle slits was made within half a beam diameter (~ 0.003 inch displacement at nozzle blade top relative to bottom). Beam displacement from the nozzle exit plane was made with the aid of calibration shims and was also true within about a half-beam diameter displacement, top to bottom. Translation of the 45° mirror results in a scanning of the vertical probe beam across a one dimensional slit nozzle flow. The detector also requires translation to maintain the probe beam signal at maximum sensitivity for the differential measurement. In tests the beam was positioned with respect to the nozzle with the 45° mirror. The detector was then positioned for maximum signal and the diagnostic adjusted for zero differential signal between the beams. The arc heated hot diluent flow was then injected into the evacuated test section and the stability of the diagnostic was verified. Introduction of SF₆ (+O₂) into the arc heater plenum resulted in the formation of F₂ near the walls. The F₂ concentration was then measured as a reduction in the probe beam intensity downstream of the walls.

The desired probe laser beam propagation contour along the 1-1/2 inch slit length is shown in Fig. 4a. The TEM_{00} Gaussian intensity profile transverse to the beam propagation direction is shown in Fig. 4b. The beam contour boundaries thus correspond to the symmetric $1/e^2$ peak intensity points of the Gaussian distribution and contain 86 percent of the beam power within them. The beam is focused so that the beam waist minimum, w_{02} , occurs at the center of the slit nozzle length. For this condition, the probe beam waist maximum w' occurs at both ends of the slit nozzle.⁽⁵⁾ w' and w_{02} are related by the equation

$$w' = w_{02} \left[1 + \left[\frac{z' \lambda}{\pi (w_{02})^2} \right]^2 \right]^{1/2} \quad (2)$$

where $z' = 1.905$ cm and $\lambda = 0.325 \times 10^{-4}$ cm in this case. The focused beam waist may be related to the lens focal length F and the laser beam divergence ($\theta_1 = 0.20 \times 10^{-3}$ rad) by the approximate expression

$$w_{02} \approx F \theta_1 \quad (3)$$

to illustrate the relation between probe beam shape in the absorption region and lens focal length.

Fig. 5 is a plot of w' and w_{02} versus lens focal length in the region of minimal achievable beam diameters. It is seen in the figure that the waist size near the slit nozzle ends reaches a minimum of $w' = 5 \times 10^{-3}$ inch diameter for a ~ 9 inch focal length lens. The waist at slit nozzle center is even smaller at $w_{02} \sim 3.5 \times 10^{-3}$ inch diameter. This is the minimum beam end

$$Z' = 0.750' \quad (1.095 \text{ CM})$$

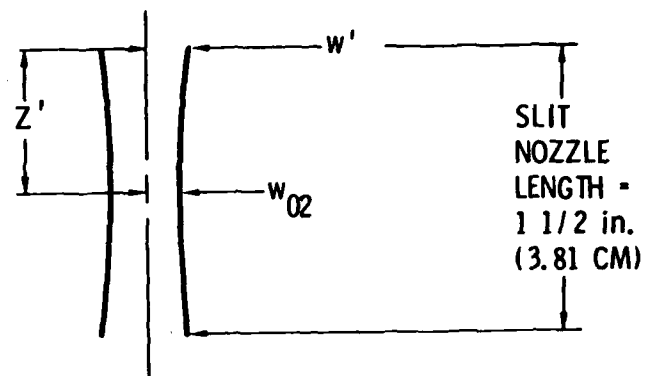


Fig. 4a. Probe laser beam geometry along slit nozzle length

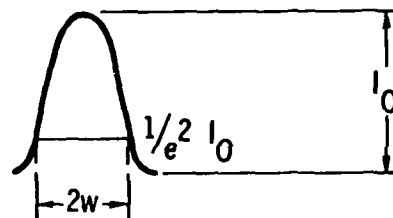


Fig. 4b. TEM_{00} Gaussian intensity profile transverse to propagation direction

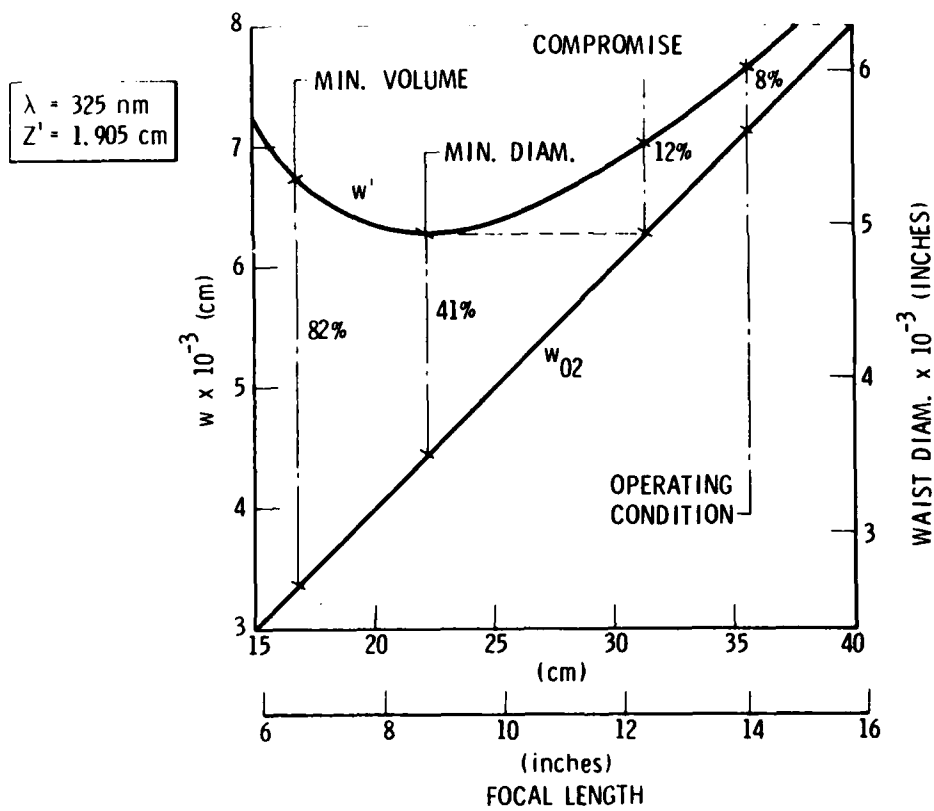


Fig. 5. Beam end waist, w' and beam center waist, w_{02} versus lens focal length

diameter that can be achieved for this experiment. However, the beam deviates somewhat from a cylindrical ideal in that the diameter of the ends is 41 percent greater than the center diameter. A closer approach to a cylindrical beam may be achieved but at the expense of increasing the beam diameter. A compromise between a small diameter beam and a small deviation from cylindrical shape may be achieved with the use of an ~ 12 inch focal length lens, as shown in the figure, which produces a center beam diameter equal to the minimum obtainable beam end diameter. Use of this lens produces a very nearly cylindrical beam with only 12 percent difference in nozzle center to end diameters. However, a longer focal length lens was required in this experiment to keep it outside the test section for ease of refined adjustment. The 14 inch focal length lens used in these experiments produced a 0.006 inch diameter beam with only 8 percent deviation from a cylindrical beam shape. Use of a 6.5 inch focal length lens results in a minimum volume probe beam, but with an 82 percent difference in nozzle center to end diameters. Lens position in the optical path must be precision calculated from well established laser divergence and lens focal length measurements to ensure accurate placement of the minimum beam waist at the slit nozzle center. See Ref. (5).

The slit nozzle array employed in these tests consisted of a set of linear slit nozzles with the dimensions 1-1/2 inch long by 0.200 inch center-to-center wide, and with a throat width equalling 0.010 inch, with secondary flow slit injection at the nozzle exits. A detail cross section drawing of the slit nozzle array is shown in Fig. 6. Arc-heated $\text{SF}_6(+\text{O}_2)$ in He diluent provided the F atom flow for the nozzle array. H_2 is injected along the trailing edges of the individual nozzles. See Fig. 7 for a photograph of the

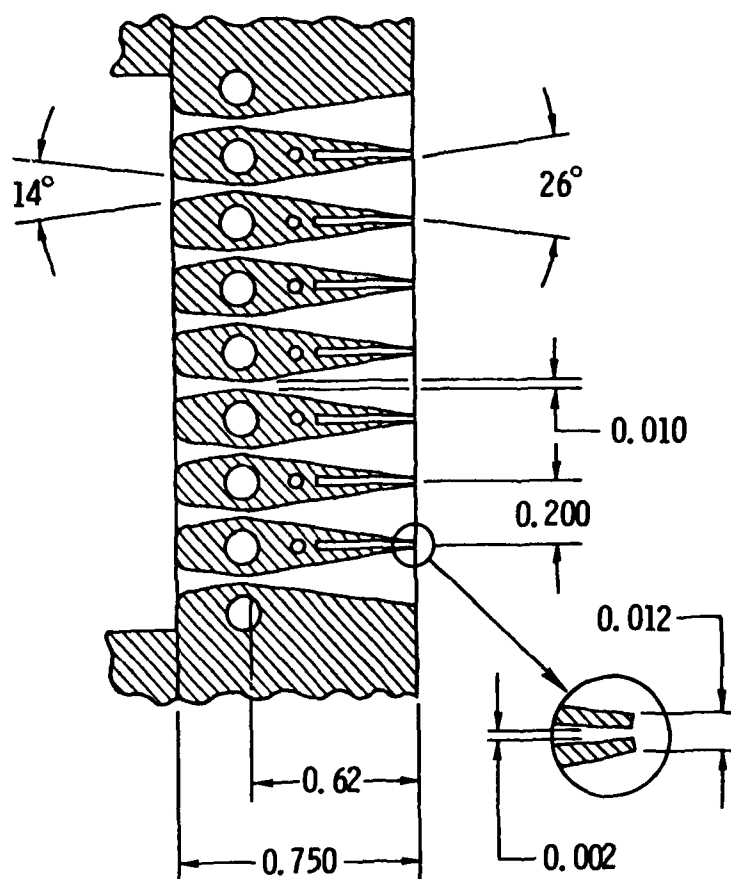


Fig. 6. Detail cross section drawing of slit nozzle array

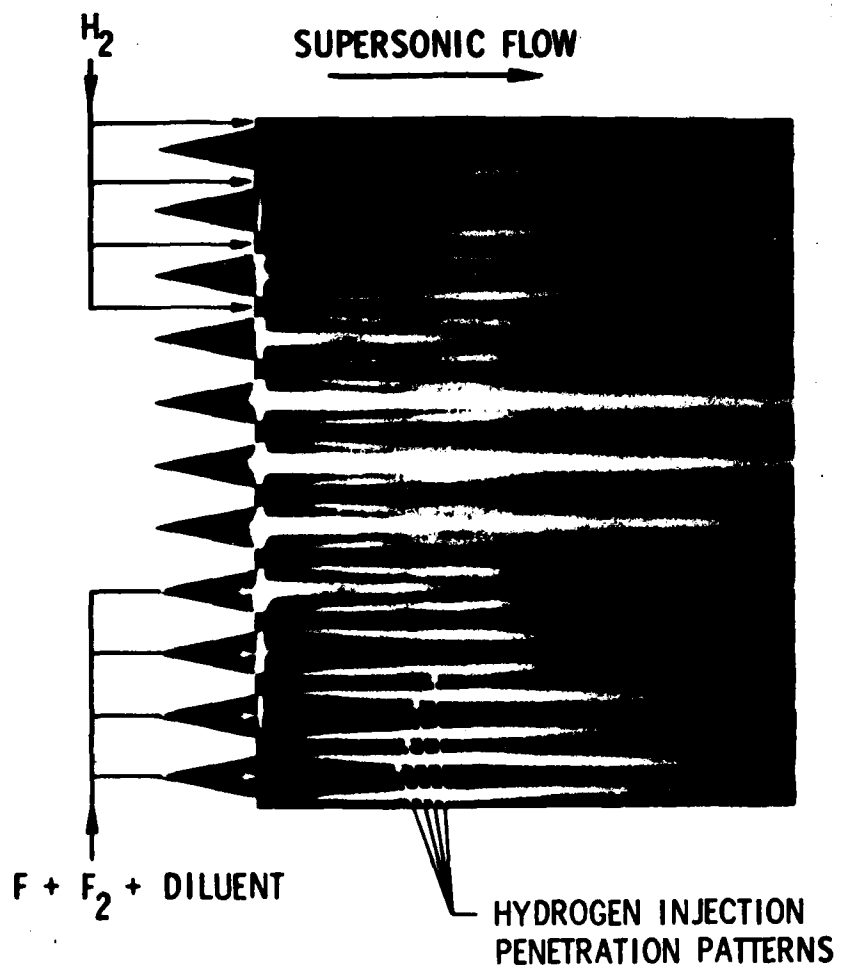


Fig. 7. Slit nozzle flow pattern

flow pattern from an array of these slit nozzles under conditions of H_2 injection into the hot flow. Note the laminar penetration pattern of the H_2 into the heated jet. The spreading rate was determined spectrographically by following the HF $P_1(6)$ line peak chemiluminescence. This measured penetration profile followed the relation $\delta = 0.1 \sqrt{x}$, in which x is the jet streamline dimension.

Flow conditions for these tests are listed in Table I where it is noted that the hot flow is principally helium. The cavity pressure was maintained at 4.5 Torr to achieve nominally matched jet conditions as determined by observation of the jet. This pressure ratio allows calculation of an adiabatic expansion helium flow Mach number of 4.3 and an equivalent area ratio of $A/A^* = 6.7$. The geometric area ratio is 19, which would yield a Mach number 6.4 flow if the nozzle were full. The equivalent area ratio is only $\sim 1/3$ the geometric area ratio, indicating the presence of a thick viscous boundary layer. This inference is in agreement with the size of the central luminous patterns relative to the individual nozzle widths associated with each hot jet, as seen in Fig. 7. Pitot pressure profiles also indicate that the core flow is $\sim 1/3$ of the nozzle flow width, i.e., each wall boundary layer is ~ 0.07 inch thick.

TABLE I. Test Flow Conditions

Molar Flow Rates

SF ₆	6.8 millimoles/sec
O ₂	6.8 millimoles/sec
H ₂	350 millimoles/sec
He	625 millimoles/sec

Pressures

Plenum	600 Torr
Cavity	4.5 Torr

Temperature

Plenum	~ 2300 K
Cavity	~ 300 K

III. RESULTS

Scanning of a single nozzle located near the center of eight 1-1/2 inch long slit nozzles was accomplished initially along a path 0.050 inch from the nozzle exit plane for conditions of (H_2OFF) and (H_2ON). The (H_2OFF) scans indicated a peak F_2 absorption directly downstream of the H_2 injection slit reducing to zero at about 0.025 inch toward the nozzle centerline. The integrated absorption curve corresponded to a ~ 50 percent recombination of F atoms in the plenum for the test conditions. This measurement was confirmatory of previous bulk measurements on cooled copper nozzle flows.⁽³⁾

(H_2ON) scans initially produced ambiguous results immediately downstream of the nozzle H_2 injection. This was demonstrated to be from probe-beam steering upon H_2 injection. This observation allowed determination of the H_2 -He penetration interface with no F or F_2 in the flow that corresponded to the penetration profile for F in the flow determined spectrographically by following the HF $P_1(6)$ line peak chemiluminescence. Inside this region (i.e., toward nozzle centerline) the F_2 absorption profile could be measured without this encumbrance and was determined to be similar to the (H_2OFF) case; the exceptions are that the profile is slightly higher in peak height, ~ 10 percent to 20 percent narrower in width, and displaced toward the centerline a distance corresponding to the H_2 penetration distance. The H_2 injection essentially displaced the F_2 boundary layer inward and compressed it in the ~ 0.07 inch thick viscous boundary layer. Fig. 8 is a presentation of this data. The data point circles are scaled to represent the 0.006 inch diameter beam size; thus, the probe beam dimension relative to nozzle size, penetration

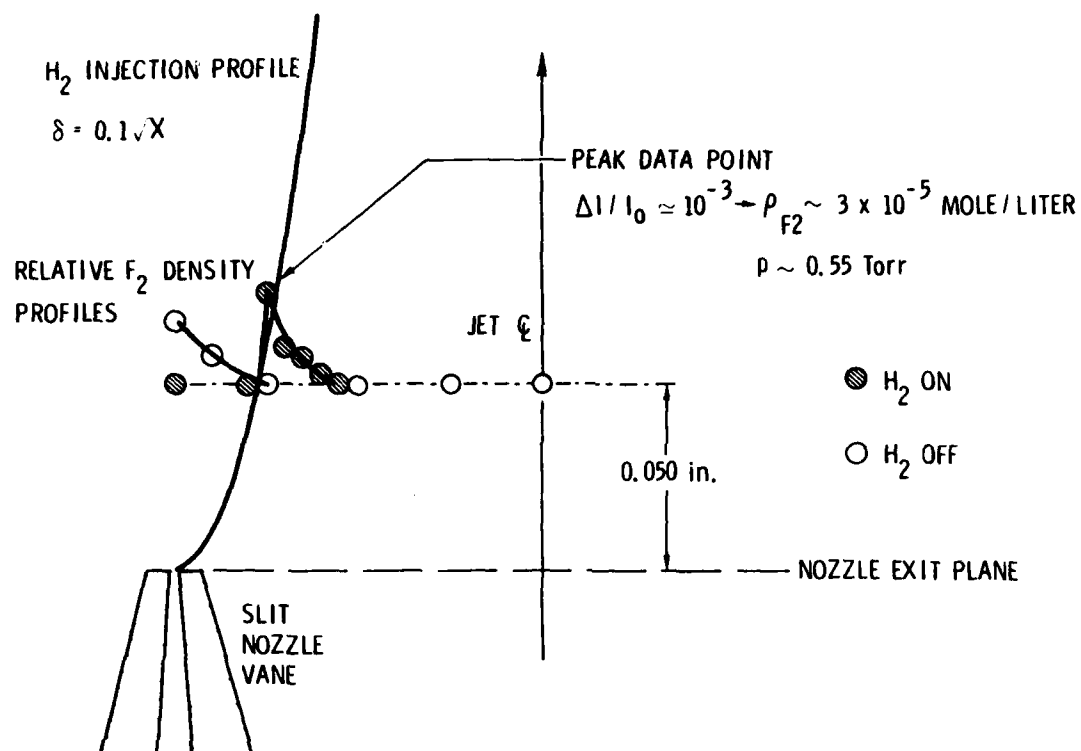


Fig. 8. Slit nozzle F_2 absorption scan along 0.050 inch line for (H_2 ON) and (H_2 Off) conditions

profile width, and F_2 boundary layer thickness can be inferred. The circles also cover the measurement uncertainties in both position (± 0.003 inch) and signal intensity ($\Delta I/I_0 \sim \pm 3 \times 10^{-5}$). The plot of data points is displaced 0.050 inch from the nozzle exit plane, which corresponds to the plane of measurement. The curves thus represent absorption values along the 0.050 inch line and should ideally be shown in three dimensions out of the plane of the drawing; however, they are folded back along the 0.050 inch line into the two dimensional representation in this figure.

The peak data point for the (H_2ON) case was measured at $\Delta I/I_0 = 10^{-3}$, a factor 33 above the minimum signal observation level. This measurement corresponds to an F_2 density of $\sim 3 \times 10^{-5}$ mole/liter or a partial pressure of ~ 0.55 Torr, i.e. $\sim 1/10$ the flow static pressure.

A scan along a line 0.030 inch downstream of the nozzle exit plane was also performed for (H_2ON) with results compatible with the 0.050 inch scan data. Data from the two scans are assembled in Fig. 9. The (H_2OFF) points obtained in the ~ 0.050 inch scan immediately downstream of the H_2 injection slit have been translated in this presentation up to the nozzle exit plane as it is assumed that the profile would have this same shape in this region of no H_2 flow. The relative F_2 density profiles are presented as in Fig. 8. The viscous boundary layer profile, as inferred from pitot pressure measurements in the jets near the nozzle, is also presented in this figure to establish the relative sizes of the F_2 and viscous boundary layers for this nozzle flow.

Measurements made near, and also 1 1/2 inches downstream from the nozzle exit plane transverse to both the flow and slit axis directions, indicated only ~ 15 percent reduction in F_2 flow concentration for the (H_2ON) condition,

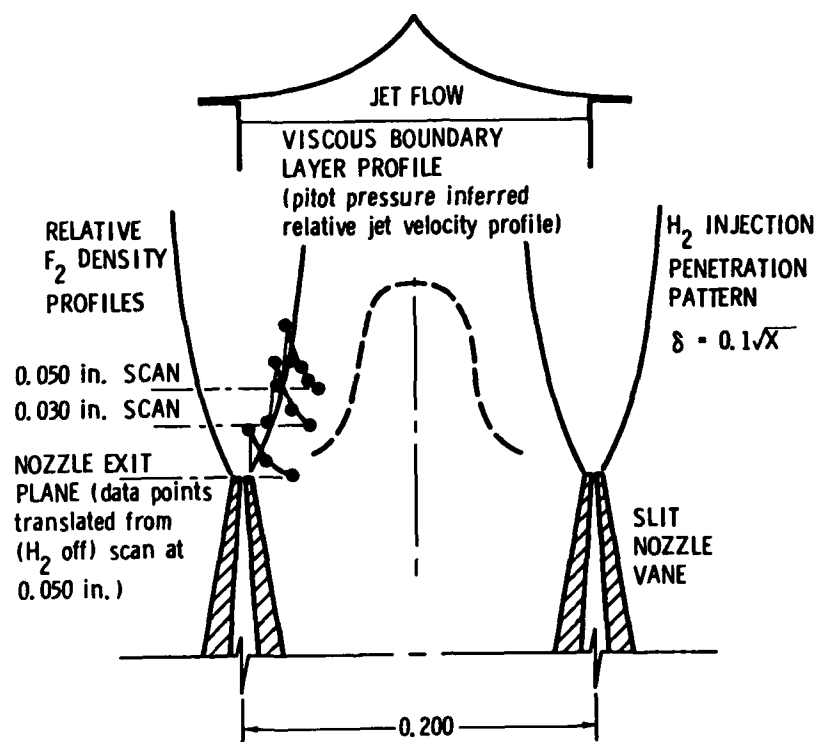


Fig. 9. Measured F₂ density profiles (relative units)

i.e., $\Delta I/I_0$ (near nozzle) = 1.2×10^{-4} , $\Delta I/I_0$ (1-1/2 inch downstream) = 1.0×10^{-4} . Thus the F_2 passed through the laser gain region essentially unreacted. The low diffusion rate of F_2 in He relative to H_2 in He (factor ~ 0.23 smaller) would indicate that the F_2 profile also passed through the laser gain region relatively intact and only slightly spread. The presence of mostly unreacted F_2 downstream of the $F + H_2$ reaction zone is consistent with the order of magnitude lower reaction rate of the $H + F_2$.⁽⁶⁾ (However, this may not be the case for higher temperature and/or lower dilution level flows where hot reaction runaway may occur.)

IV. SUMMARY

A scanning F_2 absorption diagnostic has been developed with a 0.006 inch diameter probe beam resolution over a 1-1/2 inch path length; the diagnostic has a 15 milli Torr F_2 measurement sensitivity for scanning chemical laser slit nozzle flows in order to determine the F_2 boundary layer profiles. The diagnostic was applied to a chemical laser nozzle flow and the F_2 boundary layer was determined to be of exponential decay form with peak at the nozzle wall and of width $\sim 1/3$ the viscous boundary layer. The F_2 concentration profile was displaced inwardly by the H_2 slit injection at the nozzle exit plane and apparently remained fairly intact in passing through the lasing zone. The principal deleterious effect of this F_2 concentration in the flow derived from the attendant reduced F atom concentration. For the flow conditions under test, the presence of the F_2 boundary layer had only a minor effect on H_2 mixing with F atoms; a deleterious temperature rise, which could have been produced by the hot reaction ($H + F_2$), did not develop.

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